Beyond the Standard Model

Lecture 2

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SOME QUESTIONS BEYOND THE SM

i) Values of couplings, masses and mixings

- Can they be computed in some new underlying theory?

ii) The origin of electroweak symmetry breaking

- Comes from an elementary Higgs? Composite? or?

iii) The fine-tuning problems:

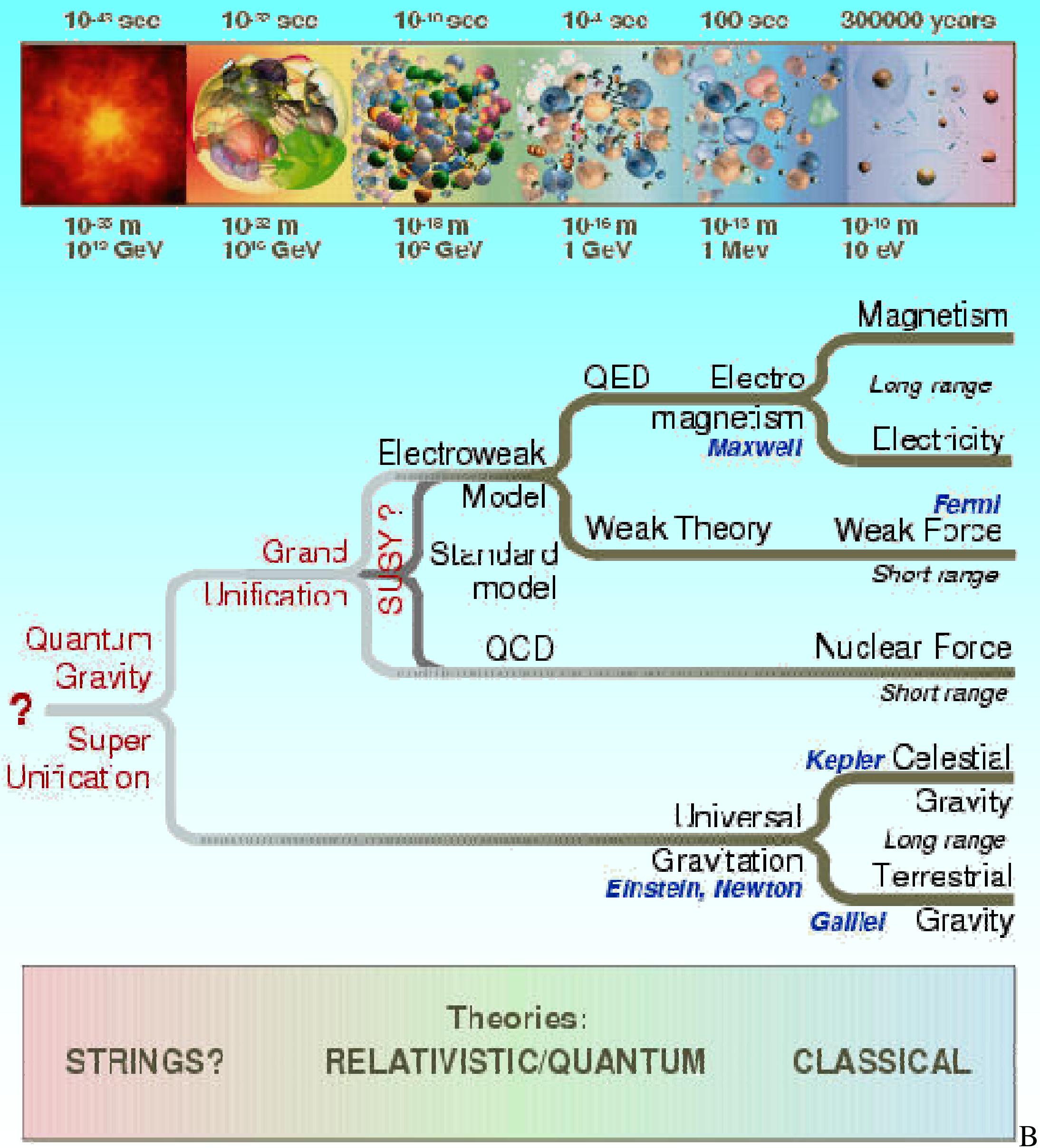
- The cosmological constant puzzle
- The strong-CP problem
- The gauge hierarchy problem

iii) Unification with quantum gravity

- String theory?

GRAND UNIFIED THEORIES

Interactions unification



GRAND UNIFICATION: SO(10)

- $SO(10) \supset SU(5) \times U(1)$
- GAUGE BOSONS: In adjoint representation, which has dimension 45 and transforms under $SU(5)$ like

$$45 \;=\; 24 + 10 + \overline{10} + 1$$

- FERMIONS: all quarks and leptons fit into a single spinorial multiplet of dimension 16

$$16 \;=\; \left(\nu_L\, u_L^1\, u_L^2\, u_L^3\, ;\, e_L\, d_L^1\, d_L^2\, d_L^3\, ;\, d_R^3\, d_R^2\, d_R^1\, e_R\, ;\, u_R^3\, u_R^2\, u_R^1 \nu_R\right)$$

$$\Longleftrightarrow$$

LEFT-RIGHT SYMMETRY

- The theory predicts the existence of a right-handed neutrino ν_R.

- GAUGE SYMMETRY BREAKING DOWN TO SM is more complicated and requires not only adjoint scalars Φ_{45} but also χ_{16} or Σ_{126}. Breaking may occur in steps

$$SO(10) \longrightarrow SU(3) \times SU(2) \times U(1)$$

$$SO(10) \longrightarrow SU(5) \times U(1) \rightarrow SU(3) \times SU(2) \times U(1)$$

$$SO(10) \rightarrow SU(4) \times SU(2)_L \times SU(2)_R \rightarrow SU(3) \times SU(2) \times U(1$$

- Electroweak symmetry breaking proceeds through scalars in the $SO(10)$ fundamental , H_{10}.
- If $SO(10)$ is broken directly to the SM the predictions are similar to those of $SU(5)$.
- In the simplest $SO(10)$ model Yukawa couplings are more constrained since there is a single Yukawa coupling

$$L^{SO(10)}_{Yuk} = Y^{ij} \overline{\psi}^i_{16} \psi^j_{16} H_{10} + h.c.$$

- This leads to a unification (at the GUT scale):

$$Y^{ij}_U = Y^{ij}_D = Y^{ij}_L = Y^{ij}_N$$

(However a single Higgs field H_{10} is not enough to get realistic spectrum since there would be no mixing).

NEUTRINO MASSES AND GUTS

- Neutral fermions like neutrinos can have three types of mass terms:

Type	Term	ΔL	ΔY
LH-Majorana	$M_L \nu_L \nu_L$	2	1
Dirac	$M_D \bar{\nu}_L \nu_R$	0	1/2
RH-Majorana	$M_R \nu_R \nu_R$	2	0

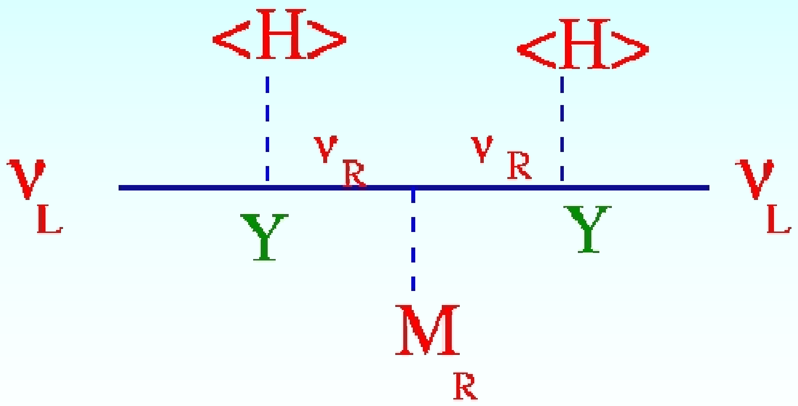
- We saw that in the SM there are only left-handed neutrinos ν_L. This means, that in the SM there are no possible Dirac masses.
- On the other hand if there is a new mass scale M_X where lepton number is broken the effective dim=5 operator may appear in the theory:

$$\frac{h_{ij}}{M_X} \nu_L^i \nu_L^j H H + h.c.$$

- Once the Higgs field gets a vev $< H >= M_W/g$, LH-Majorana neutrino masses M_L appear of order:

$$M_L^{ij} = \frac{h_{ij} < H >^2}{M_X}$$

- If $h_{ij} \simeq 1$ and $M_X \simeq 10^{14} - 10^{15}$ GeV, neutrino masses $\simeq 0.1 - 0.1$ eV's are obtained.
- GUT's provide for a natural explanation for such a large lepton number violating scale M_X [a].
- Indeed, in GUT's like $SO(10)$:
  - Lepton number symmetry is broken
  - There are right-handed neutrinos ν_R with masses of order M_X
  - The dim=5 operator mentioned above naturally appears:



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[a] Yanagida,Gelman,Ramond,Slansky (1979)

- Neutrinos may have normal Dirac mass terms M_D as any other fermion. However, since the right-handed neutrino has very large mass of order M_X, the induced Majorana mass for the left-handed ν is of order $M_L \simeq M_D^2/M_X$. This is the SEE-SAW mechanism.
- Thus one can claim that GUT's naturally predict the smallness of neutrino masses
- Many $SO(10)$ models supplemented by some extra symmetries have been proposed in order to describe the observed neutrino oscillation patterns.
- In my opinion, none of them are extremely compelling. They often include Higgs representations with 126 components and or poorly motivated non-renormalizable couplings.
- One interesting point of the see-saw models of neutrino masses is that they can give rise to the observed baryon asymmetry of the universe.
- Indeed, out-of-equilibrium decay of right-handed neutrinos can give rise to a lepton asymmetry in the universe. The latter will then be transformed by non-perturbative $SU(2)_L$ effects into a baryon asymmetry [b].
- This mechanism for generating the observed baryon asymmetry in the universe is called LEPTOGENESIS.

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[b] Fukugita, Yanagida (1986)

SUMMARY OF (non-SUSY) GUT's

- Charge quantization and the unification of quarks and leptons in simpler multiplets are very attractive.
- Also attractive is the understanding of the smallness of neutrino masses.
- However simpler non-SUSY GUT's are ruled out both by proton stability and coupling unification.
- We will see that going to SUSY-GUT's will avoid those two problems. In addition it will help in solving the notorious hierarchy problem that we will discuss soon.
- Nevertheless we will eventually see that some problems of GUT's will still remain, even in the SUSY case.
- Note also that GUT's give no clue about questions like existence of three generations or the full structure of fermion masses and mixings.
- A lot of work has been done in trying to write down models of fermion masses and mixings:

THE PUZZLE OF FERMION MASSES AND MIXINGS

- We described before the peculiar hierarchical structure of fermion masses and mixings in the SM
- We would like to have a theory of flavor explaining:
  - Why there are 3 generations
  - Why the hierarchical structure of fermion masses
  - Why CKM matrix is close to unity
  - Understand origin and size of CP violation
- At the moment we do not have a totally compelling theory of fermion masses
- There are plenty of models which combine a GUT symmetry with some flavor symmetry in generation space.
- It is impossible to review all approaches attempted.
- Let me just qualitatively describe a general approach based on flavor $U(1)$ symmetries : the Froggatt-Nielsen scenario [a].

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[a] Froggatt,Nielsen (1979);Leurer,Nir, Seiberg (1993)

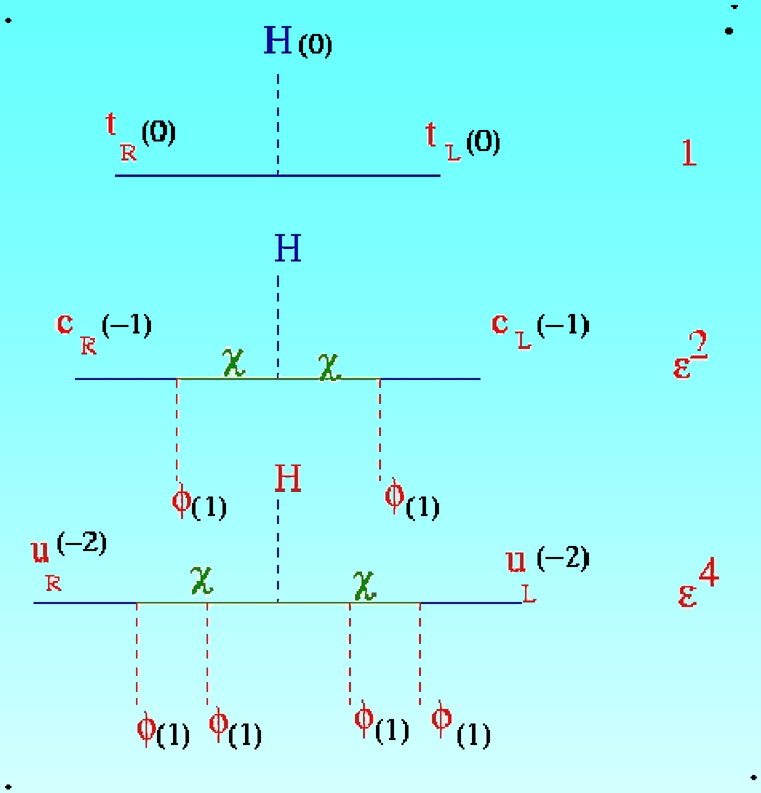
THE FROGGATT-NIELSEN SCENARIO

- The idea goes as follows: extend the SM (or a GUT) with:
  - A new gauged $U(1)$ symmetry .
  - One (or more) scalar singlet fields ϕ_{FN} charged under the $U(1)$. A vev $<\phi_{FN}>\neq 0$ breaks the $U(1)$ symmetry slightly below the GUT scale.
  - Extra fermions χ_i with masses of order the GUT scale .
- The idea is to assume that the $U(1)$ charges of quarks, leptons and Higgs are such that all standard renormalizable Yukawa couplings are forbidden except for those of the heaviest quarks and leptons.
- The lightest generations get suppressed effective Yukawa couplings from non-renormalizable couplings involving the scalar singlet field ϕ_{FN}:

$$\frac{h}{(M_X)^{n_{ij}}}\overline{\psi}_i\psi_j H_{WS}\phi_{FN}^{n_{ij}} \;\; ; \;\; i,j=1,2,3$$

- Once ϕ_{FN} gets a vev $<\phi_{FN}>=\epsilon\, M_X$, $\epsilon\simeq 0.1$, one gets effective Yukawa couplings Y_{ij}:

$$Y_{ij}\;\simeq\; h\;\epsilon^{n_{ij}}$$



- A number of models of this class have been constructed which are able to reproduce most qualitative patterns of observed masses and mixings by appropriately choosing $U(1)$ charges of SM particles.
- The $U(1)$'s are typically anomalous. Those anomalies may be canceled in the string context under certain conditions , giving rise to gauge coupling unification without a GUT symmetry.[a].

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[a] Ibanez,Ross; Binetruy,Ramond (1994)

THE FINE-TUNING PUZZLES

1) The Cosmological Constant Problem

- We know that many physical processes exist contributing the the vacuum energy.
- Consider for example the tree level Higgs scalar potential in the SM:

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

- The value of the potential at the minimum is given by

$$V_{min} = -\frac{|\mu|^4}{4\lambda} = \neq 0$$

- On the other hand Einstein's gravity equations state:

$$R^{\mu\nu} - \frac{1}{2}Rg^{\mu\nu} = -8\pi G_N <T^{\mu\nu}> = -8\pi G_N V_{min} g^{\mu\nu}$$

- where $R^{\mu\nu}$ is the Ricci tensor, $R = R^{\mu}_{\mu}$ and $T^{\mu\nu}$ is the energy-momentum tensor.
- V_{min} act as a cosmological constant: vacuum energy has a dynamical effect on space-time curvature [a].

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[a] Linde (1974);Veltman (1975)

- Cosmological data from supernovae and WMAP seem to indicate that there is a positive very small cosmological constant Λ_{cc} of order:

$$\Lambda_{cc} \sim \left(10^{-3}\, eV\right)^4$$

- This is many, many orders of magnitude smaller than the expected contribution from EW physics, of order M_W^4.
- Loop contributions to the vacuum energy diverge quartically sofine-tuning of $V_{min} = 0$ would be a extremely unnatural possibility.
- furthermore there will be anyhow very large contributions to Λ_{cc} from other processes like e.g., QCD condensation.
- The cosmological constant problem is still to be solved. Some directions considered are:
  - Modifications of Einstein's gravity at long distances
  - Quintessence scenarios
  - Use the anthropic principle.

2) The Strong-CP Problem

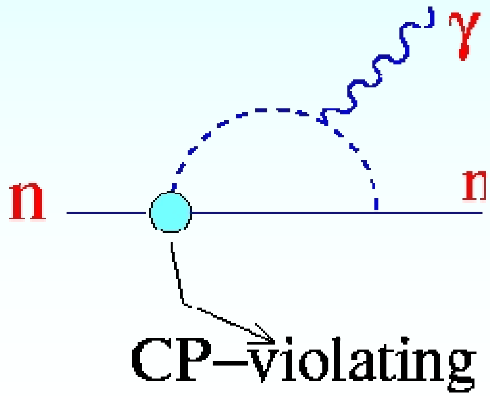
- QCD has (due to instantons) a CP-violating piece in its Lagrangian:

$$L_\theta = \frac{\theta}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

- (This is proportional to the chromomagnetic product $\vec{E}.\vec{B}$, which is explicitely CP-violating)
- Naively one would expect $\theta \simeq g_3 \simeq 1$. However such term induces very large contributions to the electric dipole moment of the neutron:

$$d_n\,(\bar{n}\gamma_5\sigma_{\mu\nu}F^{\mu\nu}n)$$

- From graphs like:



- Experimentally one has [a]

$$|d_n| < 6.3 \times 10^{-26}\, e - cm.(90\% c.l.)$$

- This implies a bound on the θ-parameter:

$$\theta \leq 2 \times 10^{-10}$$

- This is at least 10 orders of magnitude smaller than expected!.
- Unlike the case of the cosmological constant, in this case there are a few promising proposals to solve it.

The axion solution

- The idea is to introduce a new very light pseudoscalar field $a(x)$, the AXION with a coupling identical to that of the θ-parameter:

$$L_a = \frac{a(x)}{f_a 32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

- Such type of field a(x) and couplings appear if the axion is the goldstone boson of a spontaneously broken global $U(1)_{PQ}$ symmetry [b].
- The axionic coupling appears if there is a $U(1)_{PQ} - SU(3)_c - SU(3)_c$ anomaly.

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[a] Smith et al. (1990);Altarev et al.(1992)

[b] Peccei,Quinn (1977);Weinberg;Wilczek (1978).

- The SM alone does not allow for such a symmetry. One has to extend the Higgs sector by adding e.g. a scalar singlet to the SM.
- The nice point is that QCD instanton effects create a scalar potential of the form:

$$V(a) \simeq (1 - cos(\theta + a/f_a))$$

- This potential has its minimum at $\theta + a/f_a = 0$, which corresponds to vanishing effective $\bar{\theta} = \theta + a/f_a$.
- So in the axion scheme the dynamics choses the effective θ-parameter to vanish.
- The axion has mass $m_a \simeq m_\pi f_\pi / f_a$, where f_a is the scale of $U(1)_{PQ}$ breaking and $f_\pi = 93$ MeV
- There are strong astrophysical and cosmological bounds on f_a:

$$4 \times 10^9 GeV(astro.) \leq f_a \leq 10^{12} GeV(cosmol.)$$

- Thus the axion should be extremely light and very weakly coupled, couplings $\simeq m_q/f_a$. The axion is said to be 'invisible' [c].
- The axion is a candidate for dark matter.

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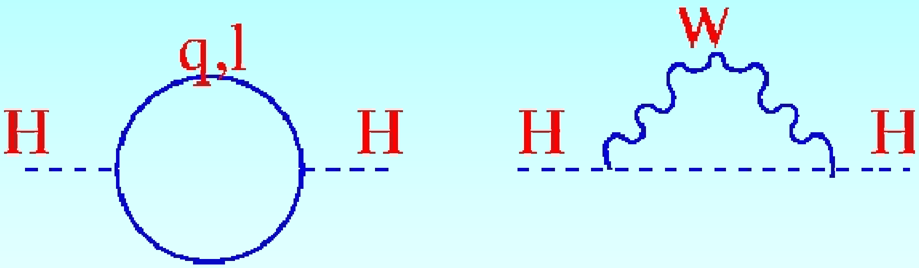
[c] Kim (1979);Shifman et al.;Dine et al. (1980)

3) The Hierarchy Problem

- A first way to present the problem is to understand why:

$$G_{Newton} \ll G_{Fermi} \;\; or \;\; M_{Planck} \gg M_W$$

- In the SM the scale of weak interactions is fixed by the mass of the Higgs field μ^2.
- Unlike fermion masses, scalar masses μ^2 recieve huge loop corrections from graphs like



- These corrections to the mass are quadratically divergent:

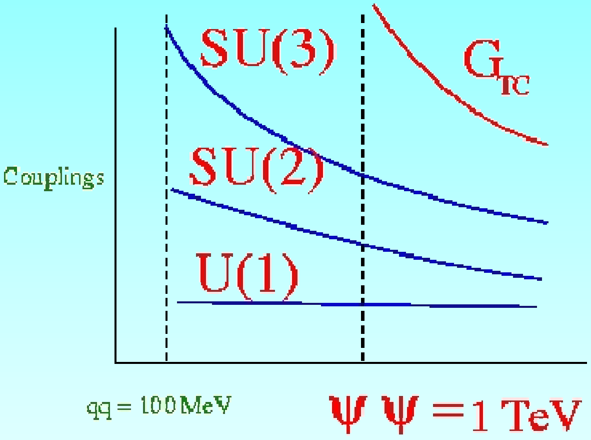
$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

- Of course, one can always renormalize the value of μ^2 so that it is small of order M_W^2. It sounds rather artificial though.

- Morover if a physical cut-off like M_p or M_{string} exists, the loop corrections will be finite and huge.
- So the question of the hierarchy problem is how to mantain the Higgs field sufficiently light to trigger EW symmetry breaking, given that its natural value would be M_{GUT} or M_p or M_{string}.
- There are a few PROPOSSED SOLUTIONS
  - Technicolor or other strongly interacting solutions
  - Low energy Supersymmetry
  - Extra dimenssions at a TeV with:
  - String scale at a TeV
  - *Little Higgs*
- Unfortunatelly I will not have time to talk about the last one.

TECHNICOLOR

- In this scheme $SU(2)_L \times U(1)$ breaking is a rescaled version up to 1 TeV of QCD chiral condensate symmetry breaking[a]
- One assumes there is a new QCD-like extra gauge interaction which becomes strong at $\Lambda_{TC} \simeq 1$ TeV:



- Instead of an elemantary scalar Higgs, the gauge symmetry is broken by a condensate of 'techniquarks' Ψ:

$$<\bar{\Psi}_R \Psi_L> \neq 0$$

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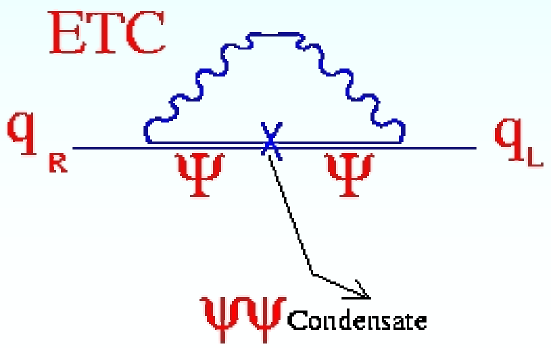
[a] Weinberg;Susskind (1975)

- This symmetry breaking gives rise to Goldstone bosons which are swallowed by the $W^{\pm}, Z^0$ to become massive.
- Since there are no elementary Higgs scalars there is no hierarchy problem. Furthermore, one can understand the hierarchy $M_p \gg M_W$ because of the running of technicolor interactions.
- Techniquarks are strongly bound by the technicolor interactions G_{TC} and form *technihadrons*. These should be produced copiously at colliders.
- The problem, as usual in BSM physics, appears in trying to give also masses to quarks and leptons.
- One has to further extend the theory with new gauge interactions connecting usual quark/leptons to techniquark/leptons,EXTENDED TECHNICOLOR (ETC):



- This gives fermion masses of order [a]:

$$m_q \simeq \frac{g_{ETC}^2}{(4\pi)^2} \frac{\Lambda_{TC}^3}{M_{ETC}^2}$$

- The problem is that in order to get quarks heavy enough the ETC scale cannot be too large.
- Since in order to get CKM mixing the ETC gauge bosons should change flavour, large FCNC above experimental bounds are typically obtained.
- In addition precision EW measurements seem to rule out too large symmetry breaking sectors, as is the case of TC and ETC

  .
- This makes the construction of viable technicolor models very difficult.

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[a] Dimopoulos,Susskind (1979)